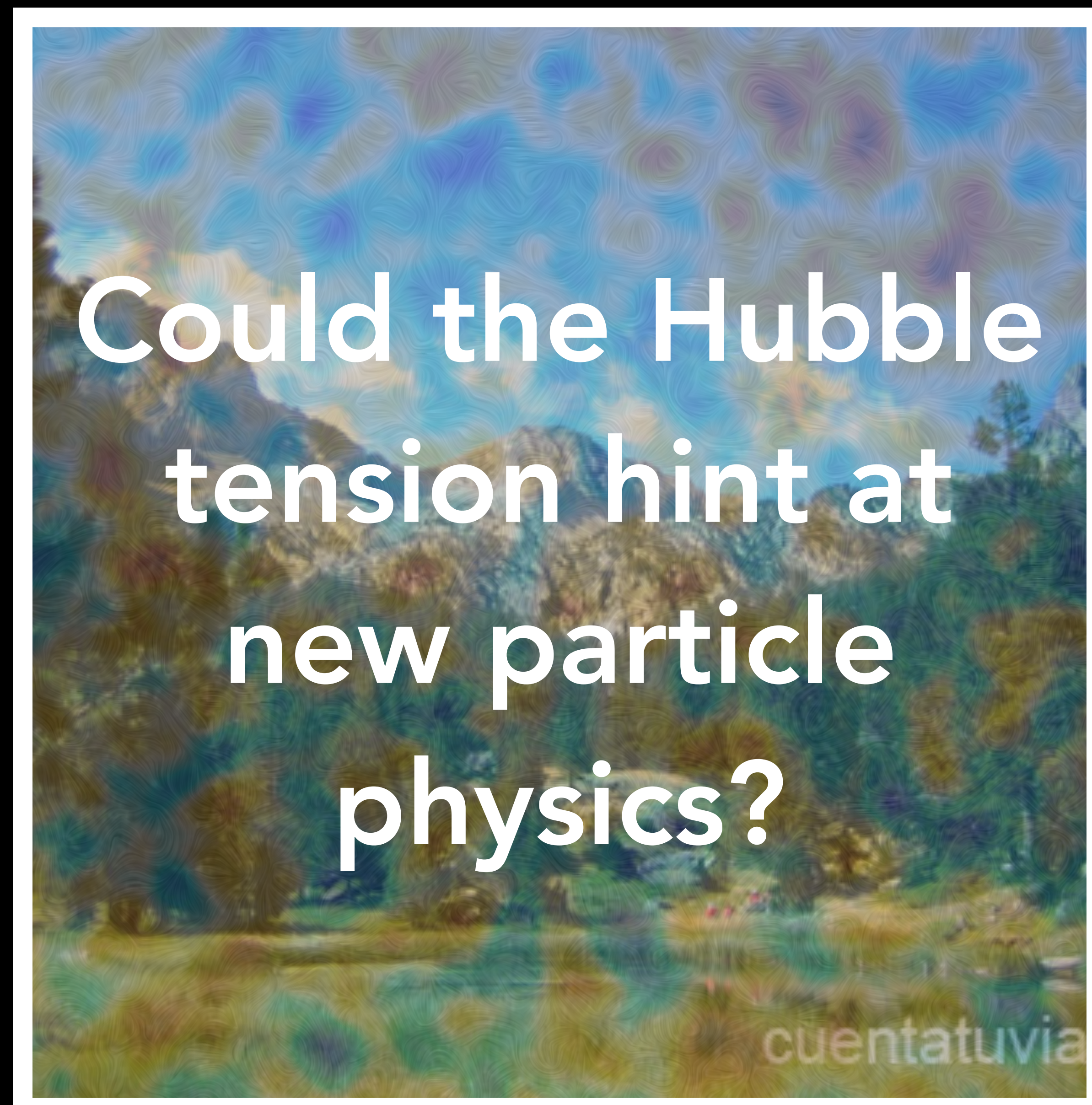
Benasque, 7.08.2019

Could the Hubble tension hint at new particle physics?



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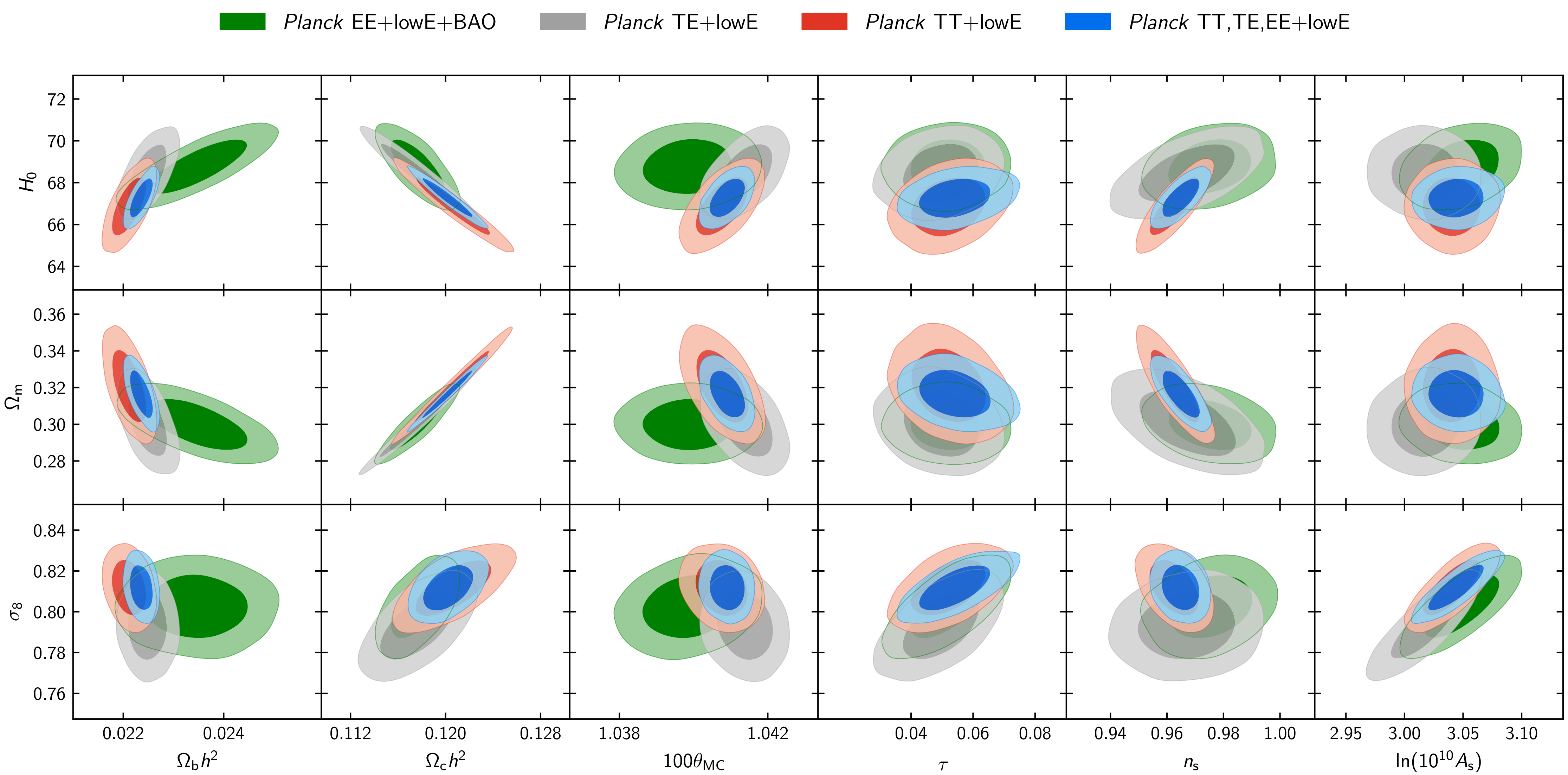
Robustness of ΛCDM

- Internal consistency of ΛCDM fit to CMB observables [Planck col. 1807.06209]

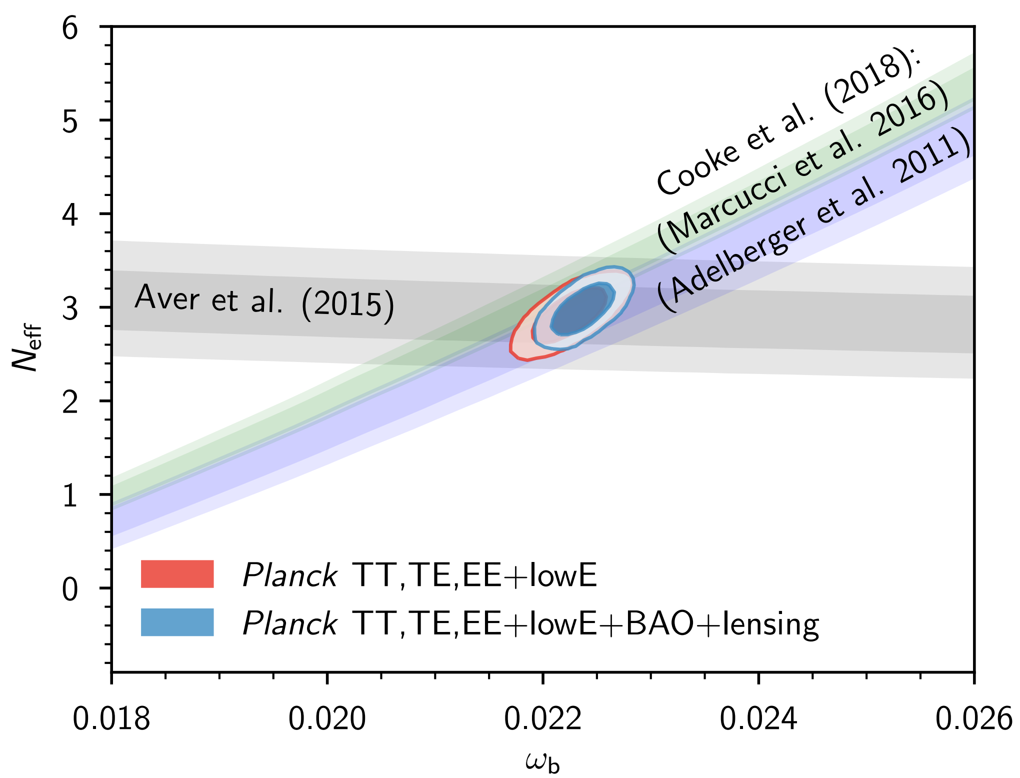


- Still: CMB data probes the universe mainly at $10^3<z<10^5$, with some sensitivity to lower redshift through: angular distance, CMB lensing, (late ISW). H_0 and σ_8 extrapolated from data+model.

Robustness of ΛCDM and Hubble tension

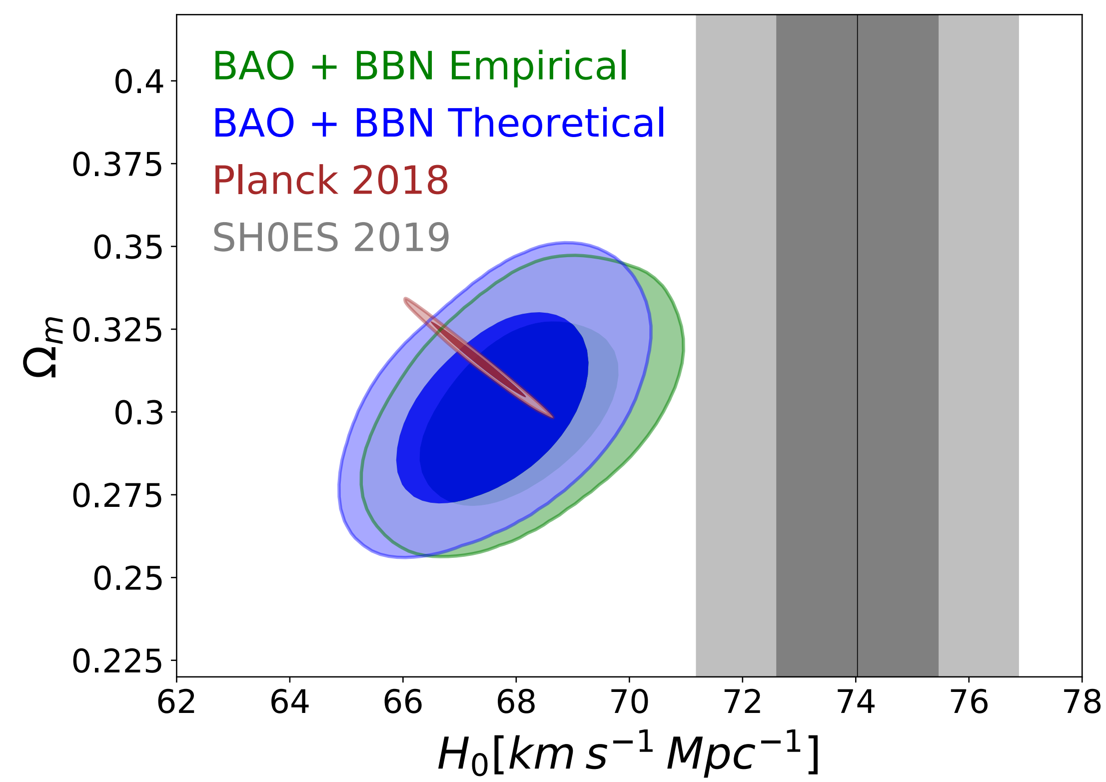
- Consistency of LCDM fit across multiple probes: CMB, BAO, BBN, distant SNIa…

He, D -> ω_b, N_{eff}



[Planck col. 1807.06209]

BAO -> H_0, Ω_m, ω_b ; BBN -> ω_b



[Cuceu et al. 1906.11628]

- Inconsistency with high H_0 measured with SNs calibrated with cepheids (HST, SHOEs). 4σ with Riess et al. 1903.07603. Quasar time-delay also prefer high H_0 and combination gives 5σ tension.

Violating the Etherington relation, or something simpler?

- BAO+BBN versus SH0ES: if all basic assumptions are correct:

standard expression for BAO scale

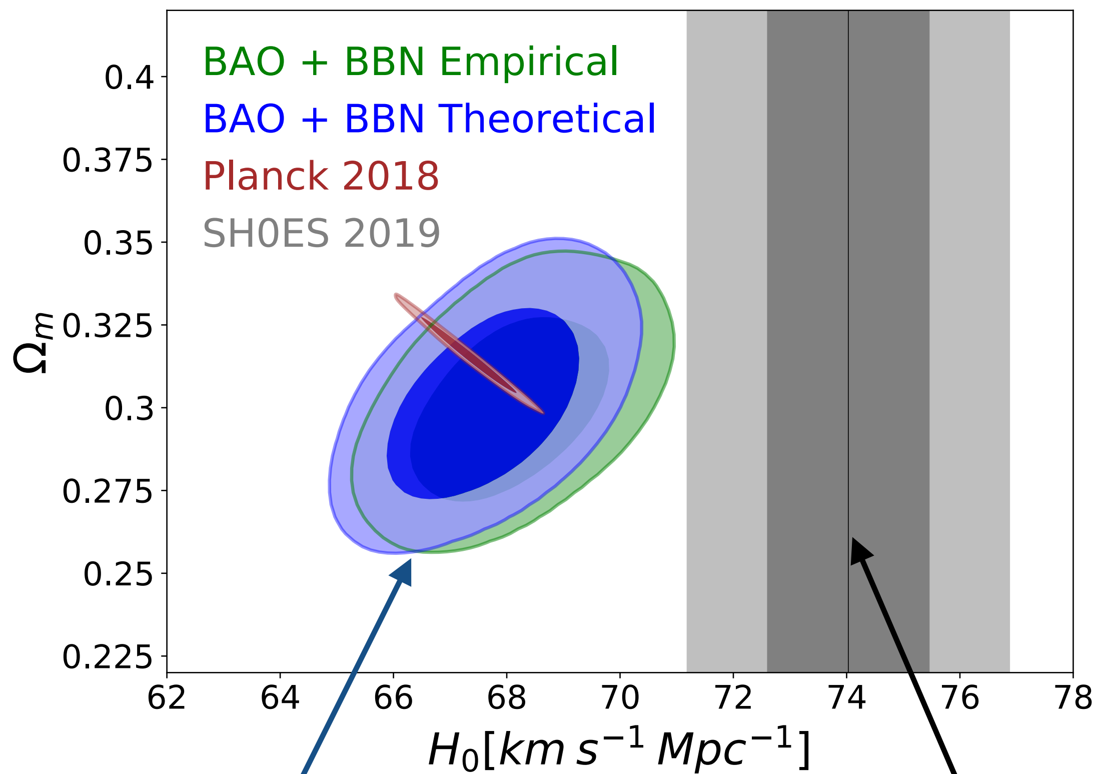
deuterium measurement and BBN calculations

cepheid calibration method for SNs

Discussed in this talk

Very well tested
see however Rigault et al.
[1412.6501,1806.03849]

[Cuceu et al. 1906.11628]



Standard rulers

Standard candles

Etherington reciprocity relation (1933) : $d_L(z) = (1+z)^2 d_A(z)$ for general metric theories of gravity
(see exceptions in Bassett & Kunz astro-ph/0312443)

Deuterium measurement and BBN calculations

- Deuterium = most robust primordial abundance measurements (> Helium > Lithium), because D not produced by stars. Converging observations:

$$10^5\, n_D / n_H = 2.527 \pm 0.030 \text{ (68 \% CL)},$$ Cooke et al. (2018)

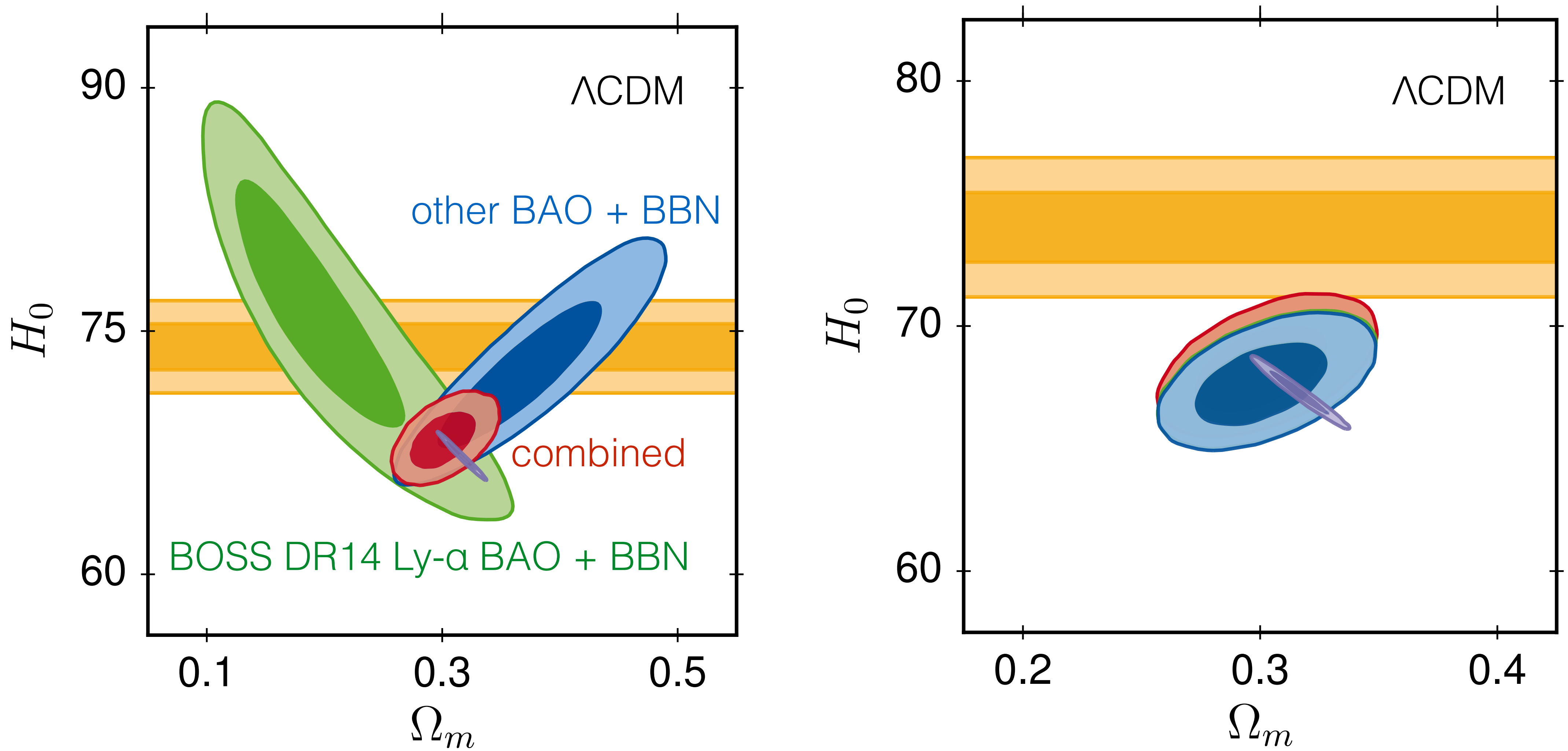
- ω_b —> BBN code —> n_D/n_H :

  uncertainties on nuclear rates: proton fusion $d(p,\gamma)^3$He , deuterium fusion $d(d,n)^3$He, $d(d,p)^3$H

Authors	Code	$d(p,\gamma)^3$He	Δy_{DP}	100 ω_b
Cooke et al. (2018)	Nollett et al.	theo.	0.02	2.166 ± 0.015 ± 0.011
Planck 2018 case (a)	PArthENoPE (Δy_{DP}=0.04)	obs.	0.06	2.270 ± 0.017 ± 0.034
Planck 2018 case (b)	PArthENoPE	theo.	0.03	2.197 ± 0.016 ± 0.016
Planck 2018 case (c)	PRIMAT (Δy_{DP}=0.015)	mixed	0.03	2.188 ± 0.016 ± 0.017

Deuterium measurement and BBN calculations

- BAO+BBN predictions for ΛCDM in Schöneberg et al. [1907.11594]



case (a): 3.2σ BAO+BBN — SH0ES tension
(3.6σ in Cuceu et al.)

cases (a), (b), (c) give the same results

Solving Hubble tension with extended cosmological model

- self-interacting active neutrinos plus Dark Radiation

  Lancaster et al. [1704.06657], Oldengott et al. [1706.02123], Di Valentino et al. [1710.02559], Kreisch et al. [1902.00534], Park et al. [1904.02625]
- light sterile neutrino interacting with a scalar field — Archidiacono et al. [1606.07673]
- Interacting Dark Matter — Dark Radiation

  Lesgourgues et al. [1507.04351], Buen-Abad et al. [1708.09406], Archidiacono et al. [1907.01496]
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- Dark Radiation from PBH — Hooper et al. [1905.01301]
- Early Dark Energy — Poulin et al. [1811.04083], Argrawal et al. [1904.01016], Lin et al. [1905.12618]
- fifth force effects on cepheids and supernovae physics — Desmond et al. [1907.03778]
- Dark Matter interacting with Dark Energy — Pan et al. [1907.07540], …
- etc. (non-exhaustive)

some models also solve σ_8 tension

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- fifth force effects — Desmond et al. [1907.03778]
- Dark Matter interacting with Dark Energy (=>w<-1) — Pan et al. [1907.07540], …
- etc. (non-exhaustive)

change BAO scale (but not angle)

change $d_A(z)$,$d_L(z)$ only at very small z

change standard candle physics

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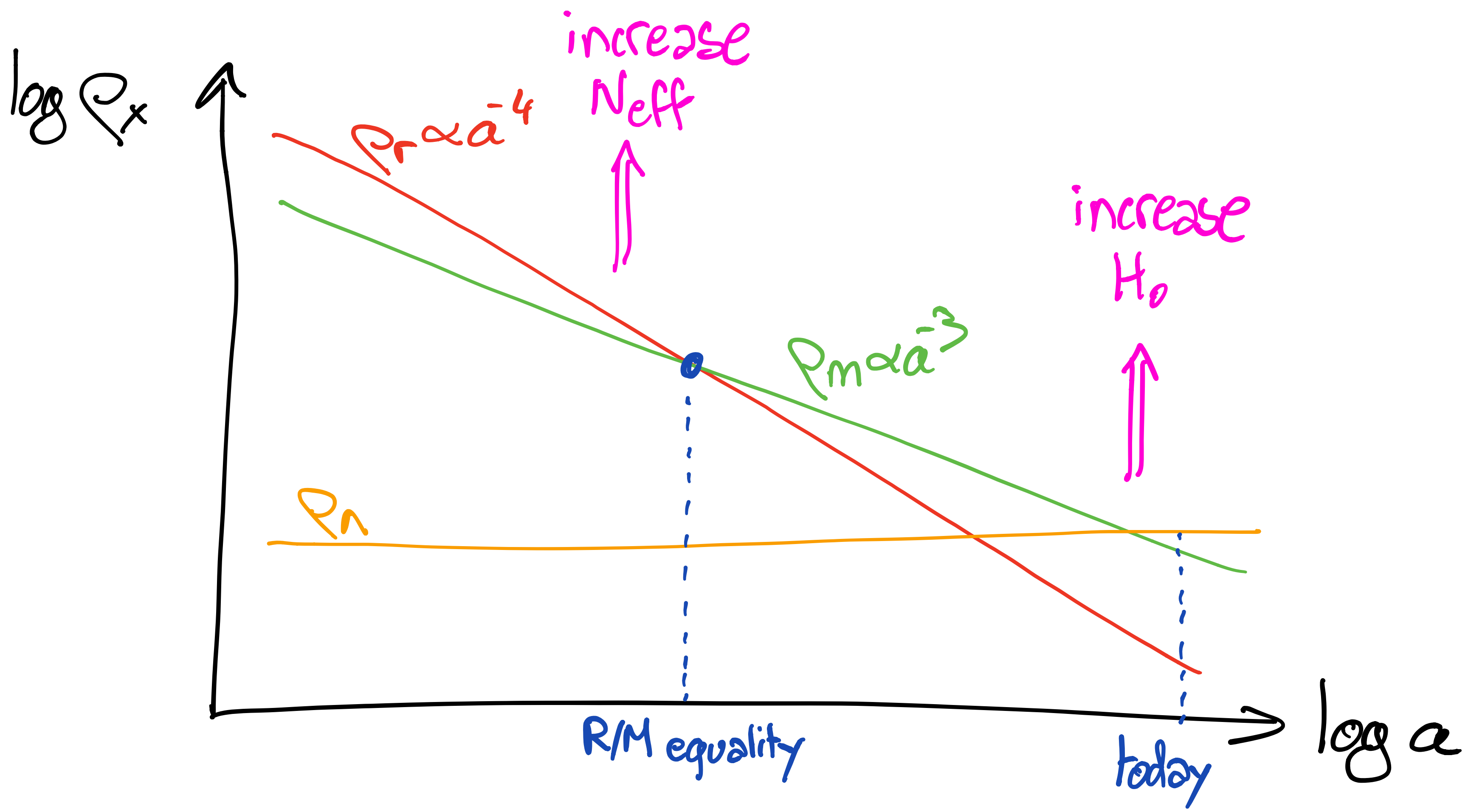
$N_{eff}>3$ (green) other form of energy excess around equality (red)

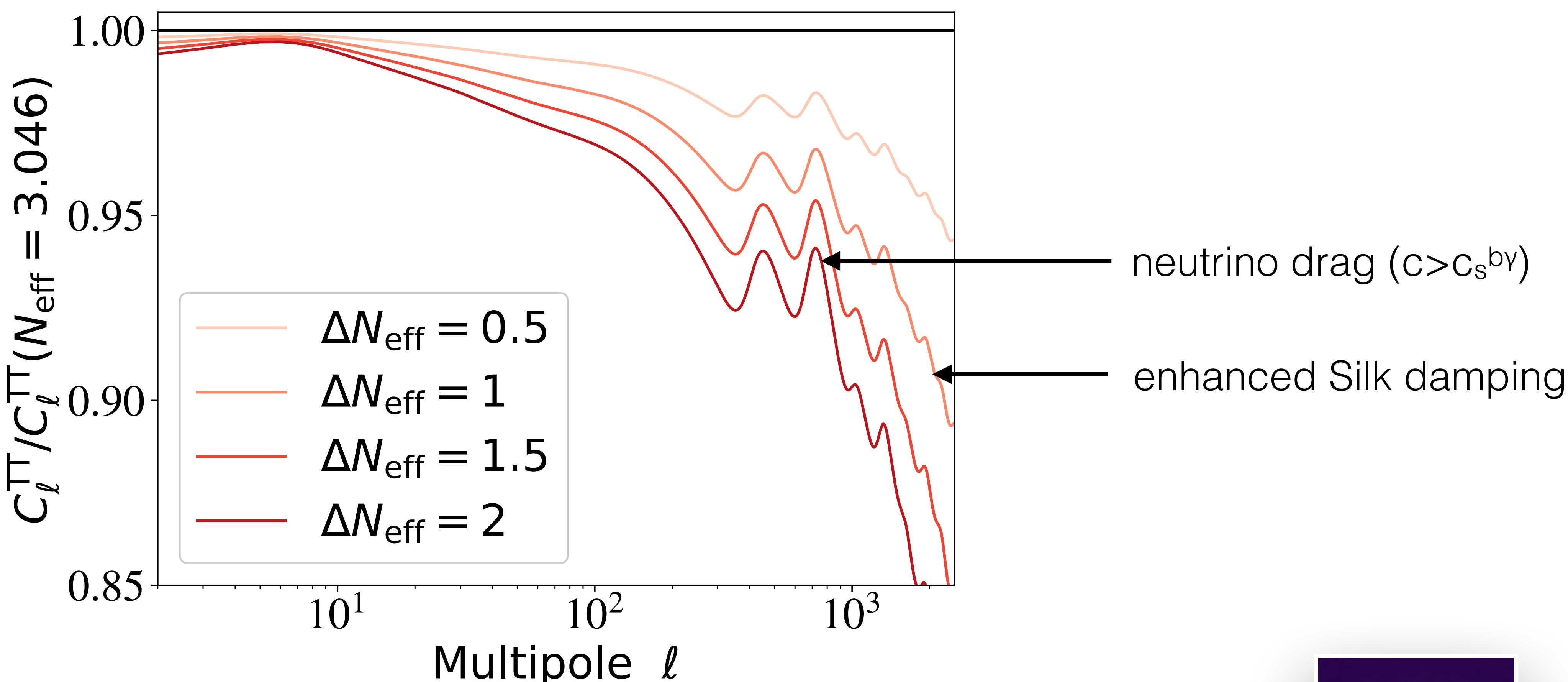
The H_0 - N_{eff} (partial) degeneracy

- Observations (CMB, BAO, LSS…) mainly sensitive to ratios:
  - ρ_m / ρ_r => $\omega_m / \omega_r = \Omega_m / \Omega_r$ => z_{eq}
  - ρ_Λ / ρ_m => $\Omega_m = 1 - \Omega_\Lambda$ => z_Λ
- Fixed Ω_m: H_0 governs absolute matter and Λ density today, $\rho_m \sim \Omega_m H_0^2$, $\rho_\Lambda \sim \Omega_\Lambda H_0^2$
- May increase (H_0, N_{eff}) last same time with fixed z_{eq}



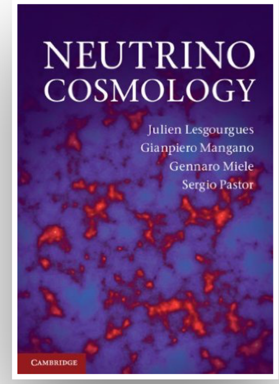
The H_0 - N_{eff} (partial) degeneracy

- So, high H_0, N_{eff}~4 (e.g. light sterile neutrino), and that's it?
- NO! Increasing (H_0,N_{eff}) has other (bad) effects: CMB damping tail, neutrino drag on CMB peaks,



[PDG review on Neutrinos in Cosmology, J.L. & L.Verde]

also Bashinsky & Seljak 03, Hou et al. 11, Neutrino Cosmology (2013) JL et al.



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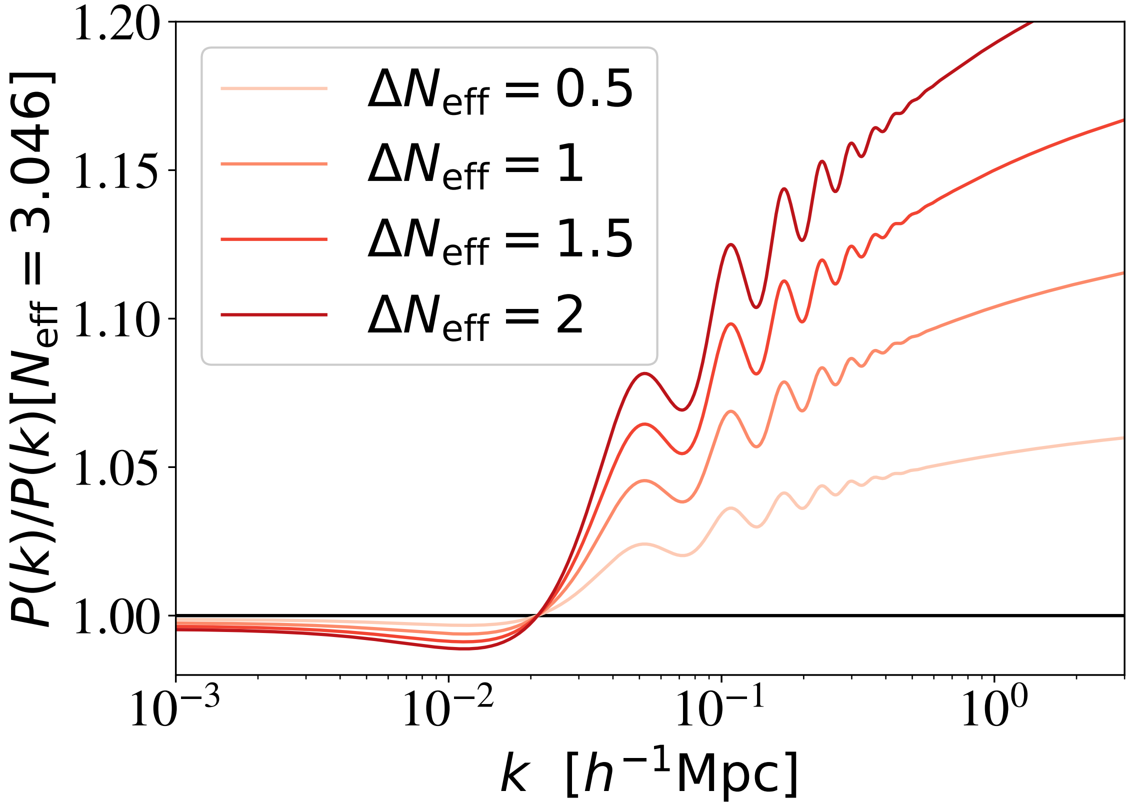
- $\Omega_m h^2 = \Omega_b h^2 + \Omega_{cdm} h^2$. CMB also fixes $\Omega_b h^2$ so Ω_b/Ω_{cdm} changes. Small-scale matter power spectrum enhanced.



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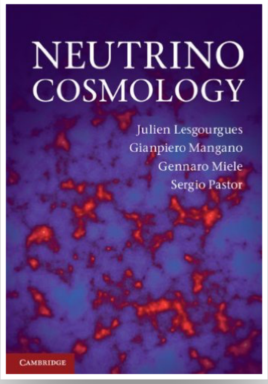

The H_0 - N_{eff} (partial) degeneracy

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- $\Omega_m h^2 = \Omega_b h^2 + \Omega_{cdm} h^2$. CMB also fixes $\Omega_b h^2$ so Ω_b/Ω_{cdm} changes. Small-scale matter power spectrum enhanced.
- "bad effects" can be reduced by exotic physics:
    - extra radiation is self-interacting -> no neutrino drag;
    - radiation remains more clustered during RD -> less Silk damping;
    - Matter clusters less during MD -> no power spectrum enhancement…

Constraints on background cosmology with enhanced Neff

- Can test *only the background evolution* in these models?

—> independently of perturbations, scattering, self-interactions…

—> N_{eff} from free-streaming (v=c) or self-coupled (c_s^2=1/3) relativistic species…

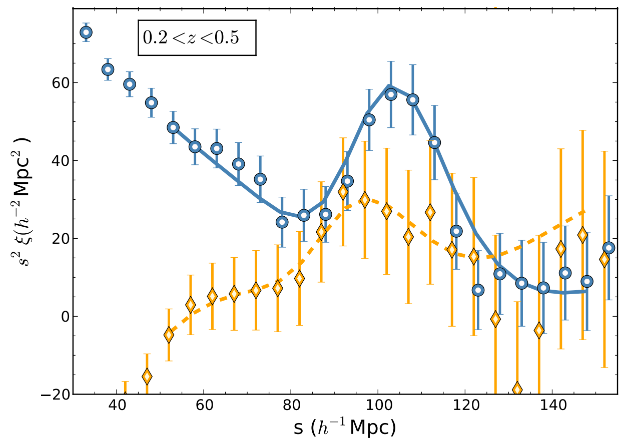
- BAO data test the background evolution :

$$\theta(z) = \frac{r_s(z_D)}{r_A(z)}$$

  - not so obvious… [Thepsuryia & Lewis 1409.5066; Schöneberg et al. 1907.11594 Appendix A]

BAO scale in correlation function

(gravity+pressure; neutrino drag…)



sound horizon

(pressure only)

$$r_s(z_D) = \int_0^{\tau_D} c_s(\tau)d\tau = \int_0^{t_D} \frac{dt}{3a(t)\sqrt{1+R(t)}}$$

$$R = \frac{3\rho_b}{4\rho_\gamma}$$

Ratio of the two could depend on cosmology (e.g. on N_{eff} of free-streaming species)

N_{eff} 3 —> 4 : ratio increases by 0.1%; BAO errors: 0.9% ; so sound horizon OK as a proxy!

Constraints on background cosmology with enhanced Neff

- Can we find test background evolution in these models?

—> independently of perturbations, scattering, self-interactions…

—> N_{eff} from free-streaming (v=c) or self-coupled (c_s^2=1/3) relativistic species…

- BAO data test the background evolution

- BAO —> H_0, Ω_m, ω_b ; no H_0 constraint without ω_b prior

    - BAO + ω_b from CMB? No, ω_b degenerate with perturbation-related ingredients

    - BAO + ω_b from BBN? Yes!

- *The BAO+BBN take on the Hubble tension* [1907.11594]

with Nils Schöneberg Deanna Hooper

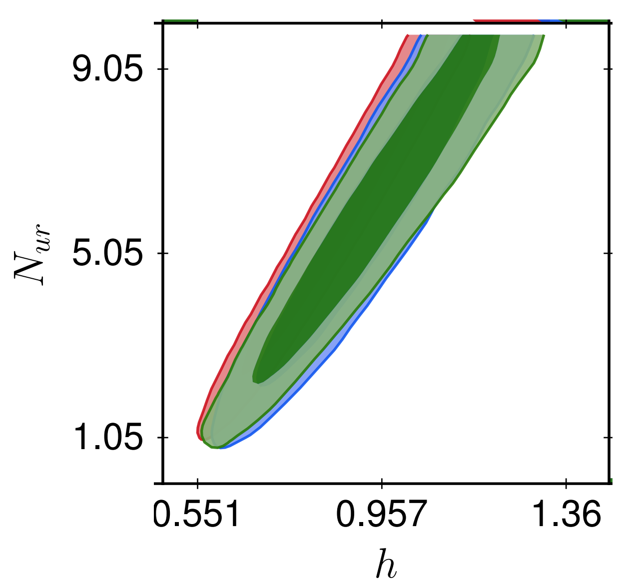
Constraints on background cosmology with enhanced Neff

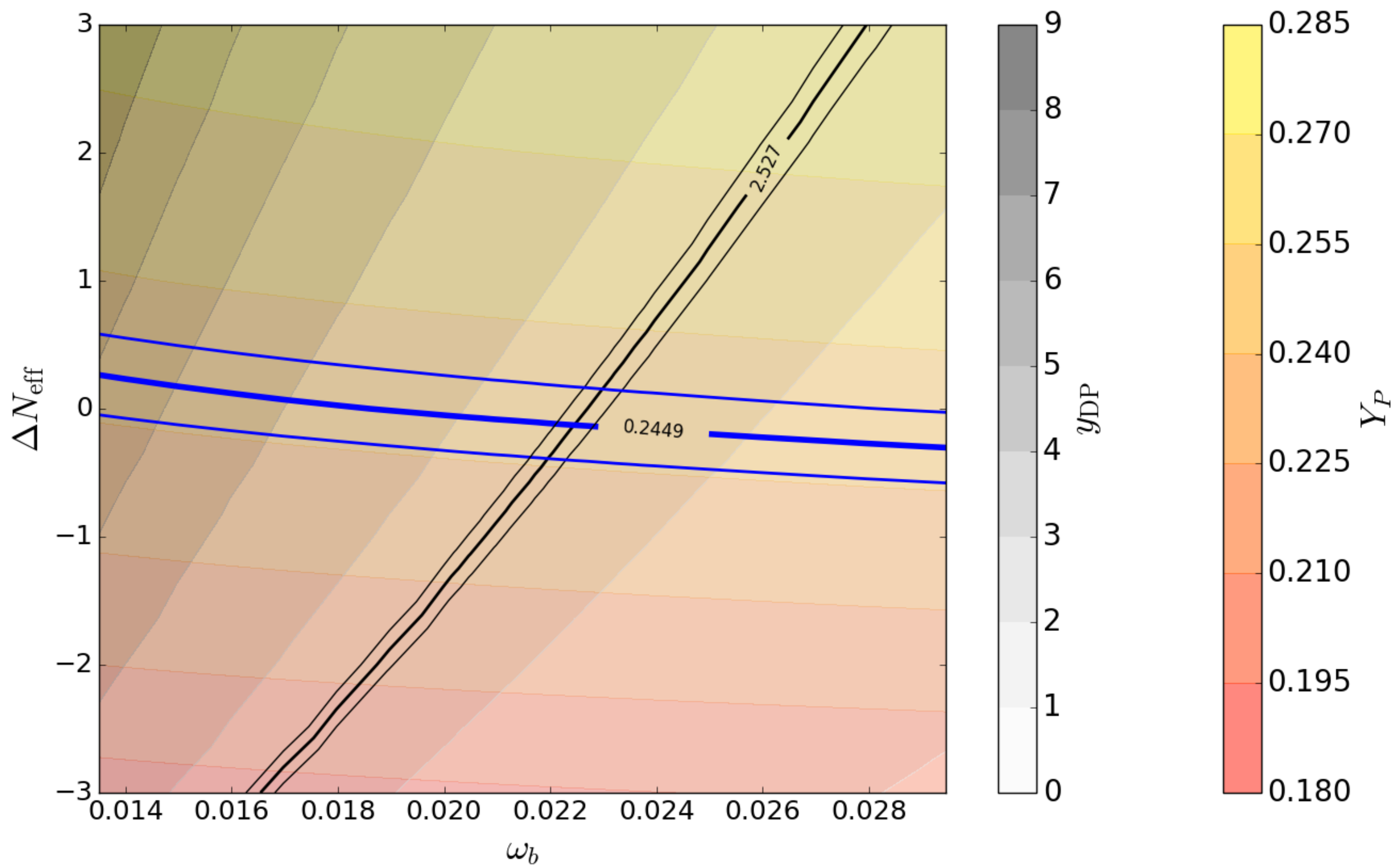
- Deuterium only : allows arbitrary variations in H_0 , N_{eff}

$$\theta(z) = \frac{r_s(z_D)}{r_A(z)} \simeq \frac{\int_{z_D}^{\infty} c_s(\omega_{\rm b}, \tilde z)\left[\Omega_{\rm r}/\Omega_{\rm m}(1+\tilde z)^4 + (1+\tilde z)^3\right]^{-1/2} d\tilde z}{\int_0^z \left[1/\Omega_{\rm m} - 1 + (1+\tilde z)^3\right]^{-1/2} d\tilde z}$$

N_{eff} increases —> ω_b increases,

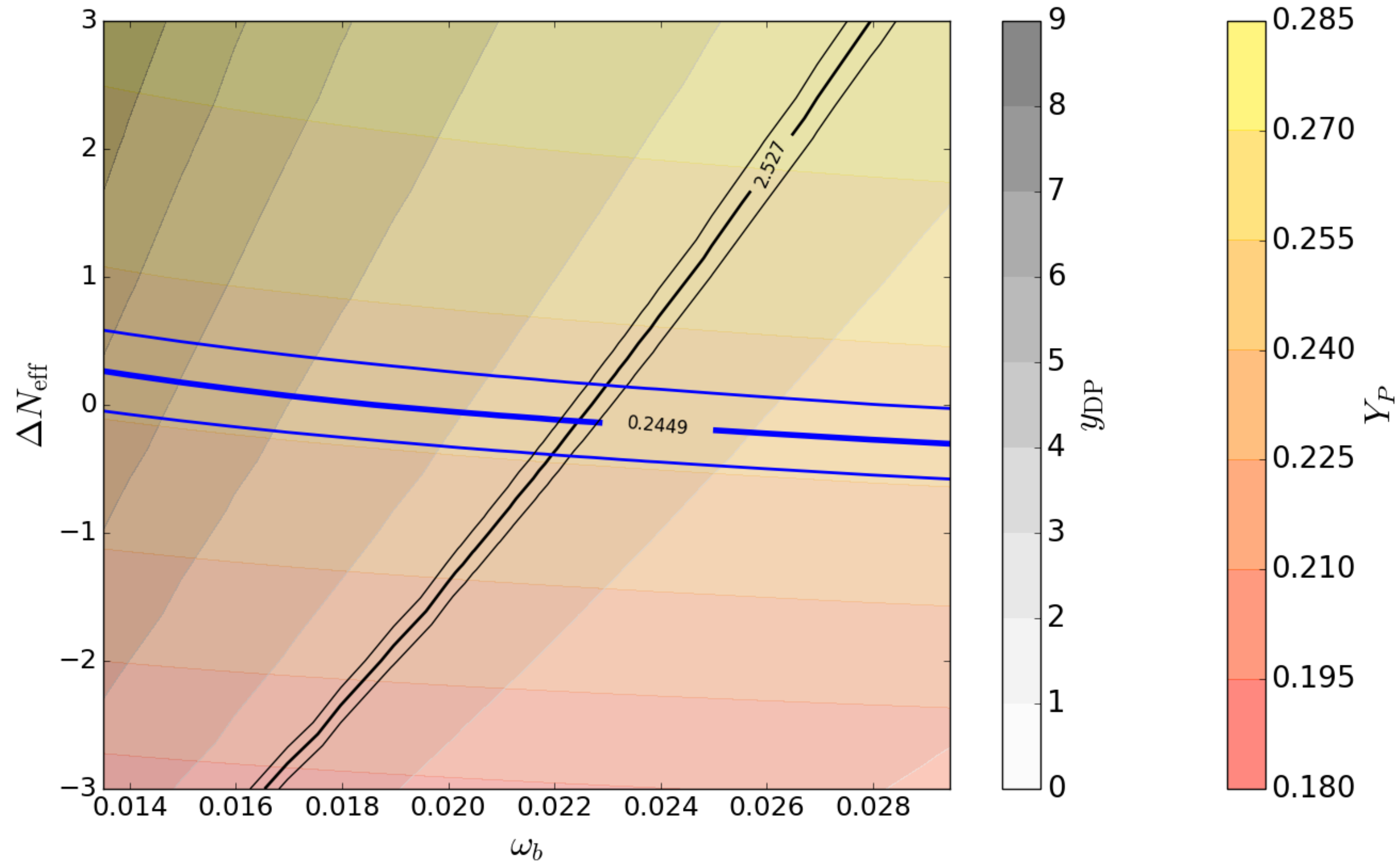
but small and can be adjusted





Constraints on background cosmology with enhanced Neff

- Adding Helium constraints?

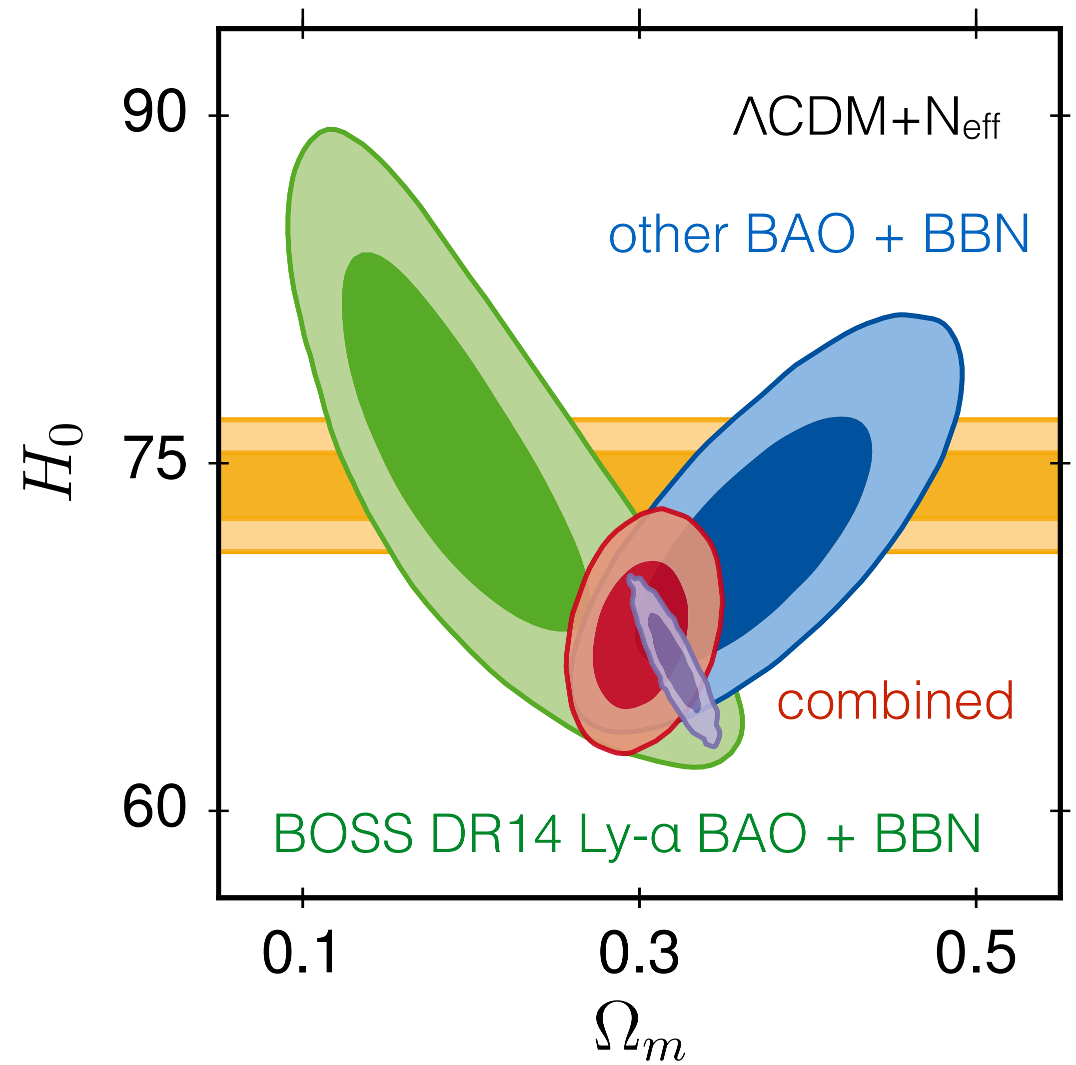


- If $N_{\rm eff}\approx 3$ at BBN and $\Delta N_{\rm eff}$ generated between BBN and equality: still no constraint (e.g. DM annihilating into DR, 1712.01246, 1803.03644)

- If $N_{\rm eff}$ is constant between BBN and CMB:

$$\text{Helium} \xrightarrow{\text{BBN}} N_{\rm eff} \text{ bounds} \xrightarrow{\text{BAO}} H_0 \text{ bounds (independent of perturbations)}$$

Constraints on background cosmology with enhanced Neff



[Schöneberg et al.1907.11594]

- Tension BAO+BBN <—> SH0ES reduces from 3.2σ to 2.6σ level only!
- $H_0 = 67.7^{+2.0}_{-2.2}$ km/s/Mpc (68% CL)
- Could be enough if H_0↘ (star formation bias), otherwise: N_{eff} produced late or radically different mechanism…

Solving Hubble tension with extended cosmological model

- self-interacting active neutrinos plus Dark Radiation

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- Dark Matter converting into Dark Radiation — Slightly better than ΛCDM+N_{eff} by tuning annihilation history

  Poulin et al. [1606.02073], Binder et al. [1712.01246], Bringmann et al. [1803.03644]

- Dark Radiation from PBH — No better than ΛCDM+N_{eff} — Hooper et al. [1905.01301]
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- etc. (non-exhaustive)

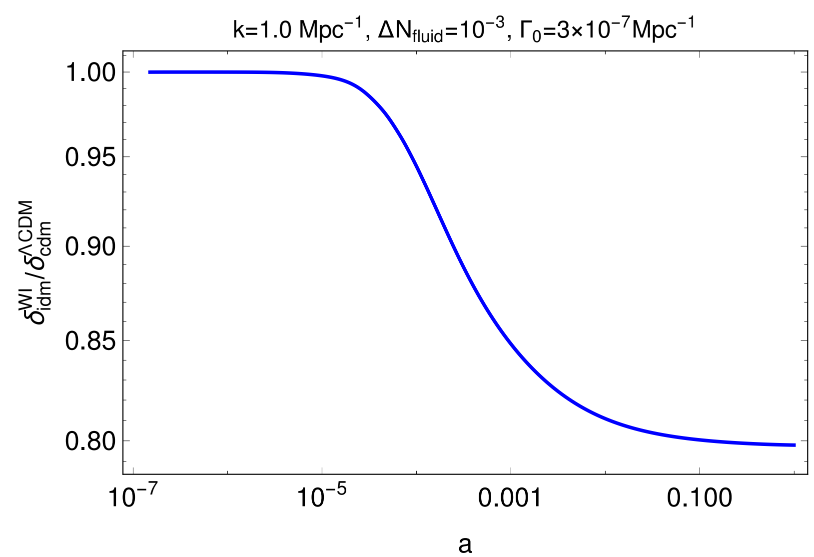
$N_{eff}>3$ (green)   other form of energy excess around equality (pink)

Interacting Dark Sector

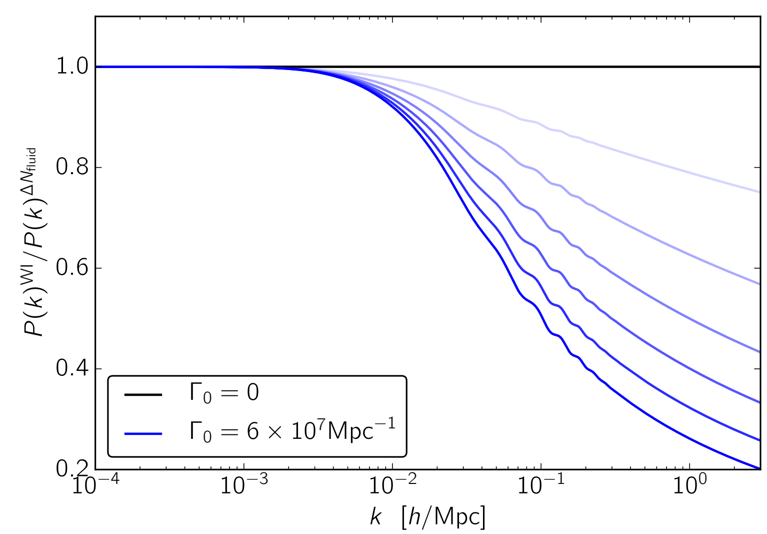
Particle physics: Buen-Abad, Marques-Tavares, Schmaltz, 1505.03542; <— LHC-motivated
Cosmo: Lesgourgues et al. 1507.04351; Buen-Abad et al. 1708.09406; Archidiacono et al. 1907.01496

- DM and DR = relics from a Dark Sector (dark symmetry, massive fermions, dark photons or dark gluons), DR = self-coupled fluid enhancing N_{eff}

- DM-DR momentum exchange rate ~ T^2,
  Γ/H = constant during radiation era,
  constant small dragging of DR over DM,
  DR growth rate enhanced,
  DM growth rate reduced



- “bad effects” of high Neff on CMB cured by DR sound speed and perturbations / on P(k) cured by DR drag on DM, even σ8 reduction!



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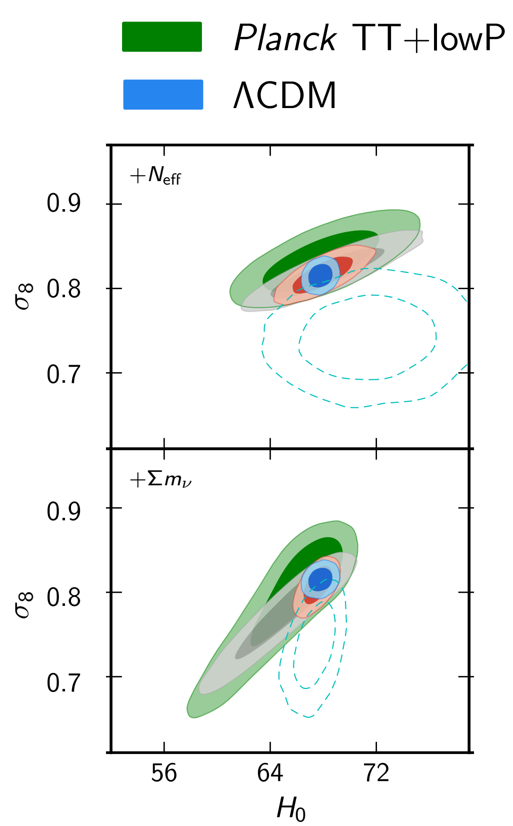
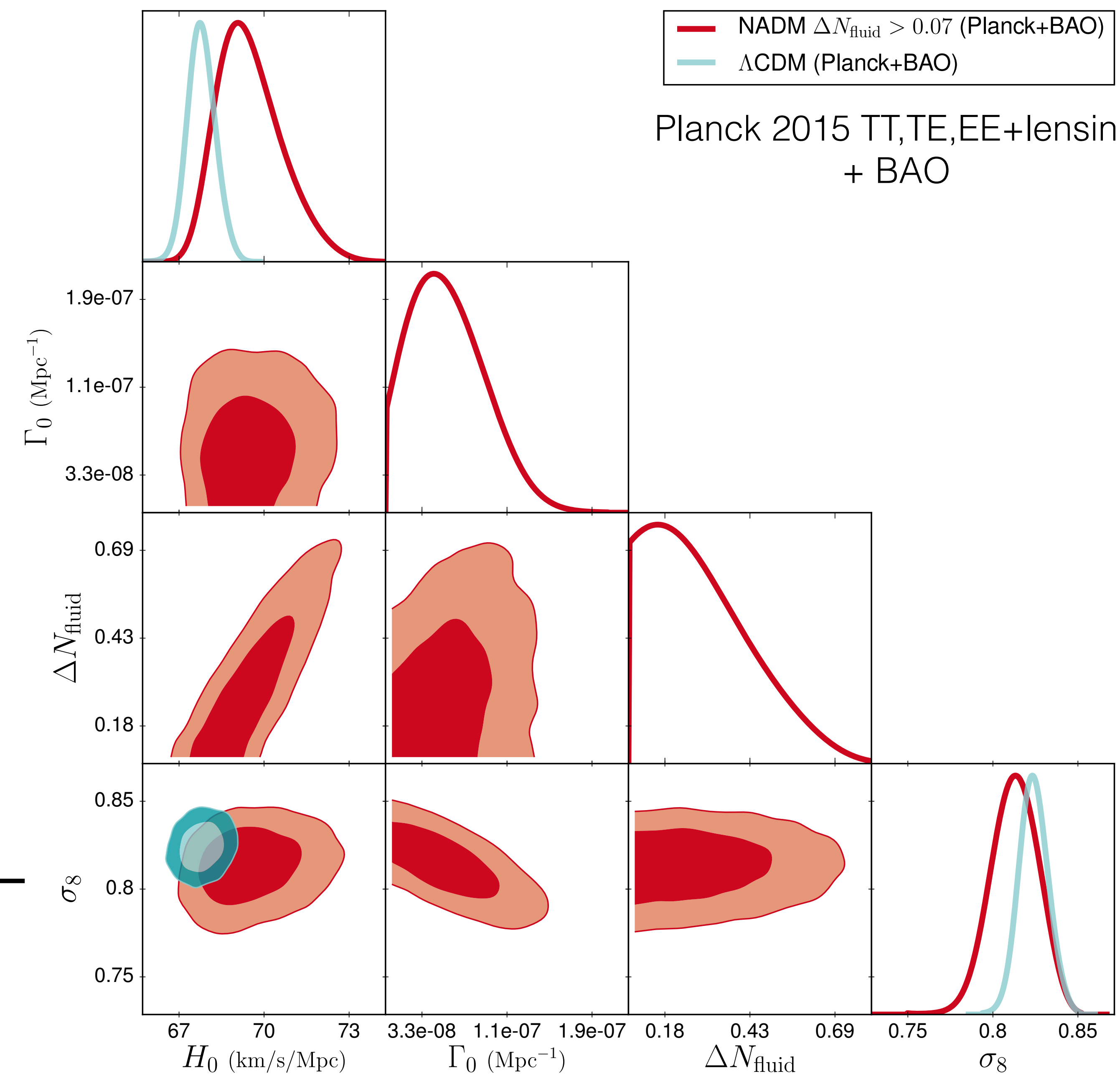
Large values of ΔN_{fluid}

ease both Hubble and σ_8 tensions :



[Planck 2015 parameters]

compare with



DM-DR interaction DR density

Interacting Dark Sector

Particle physics: Buen-Abad, Marques-Tavares, Schmaltz, 1505.03542;
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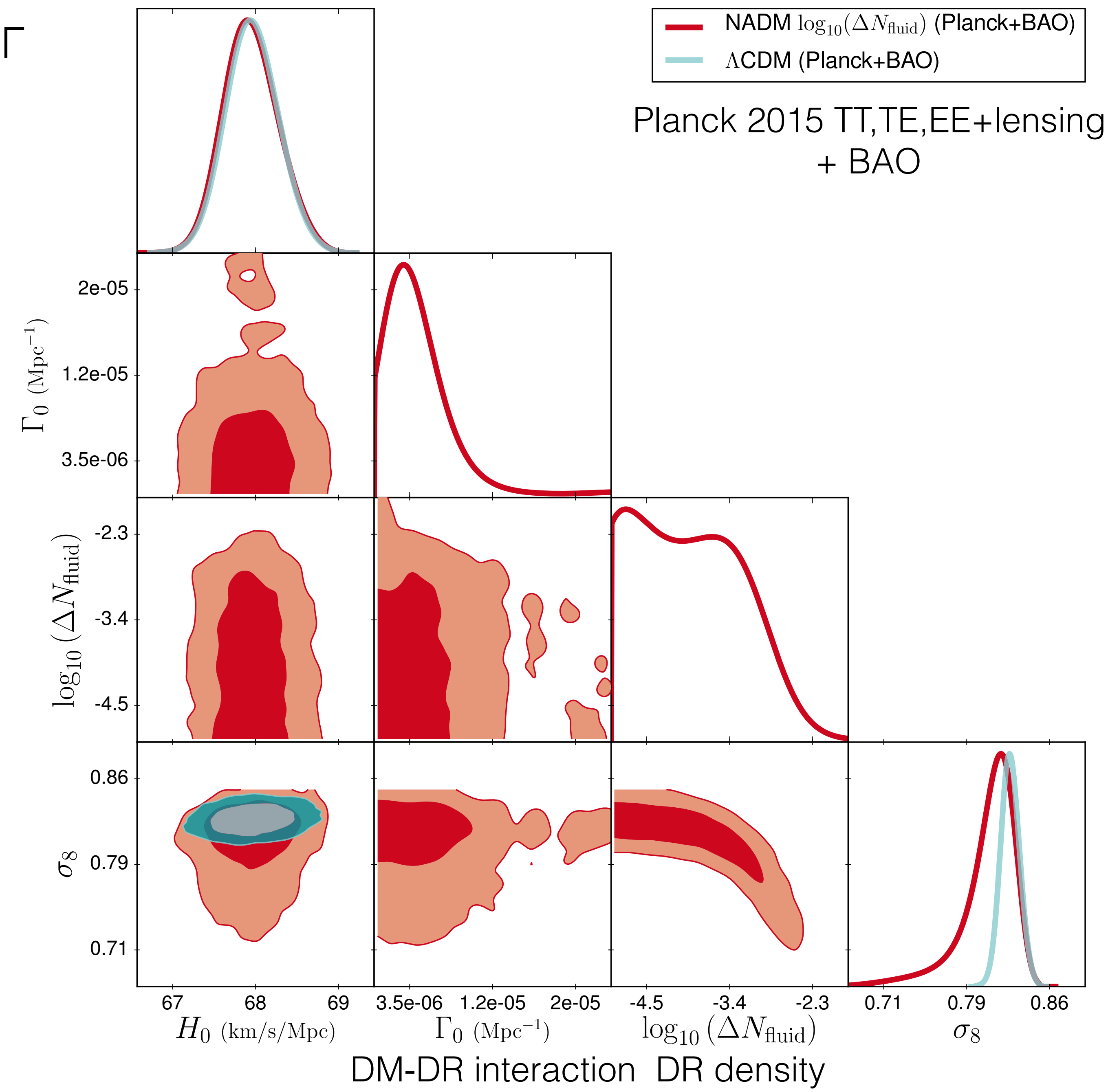
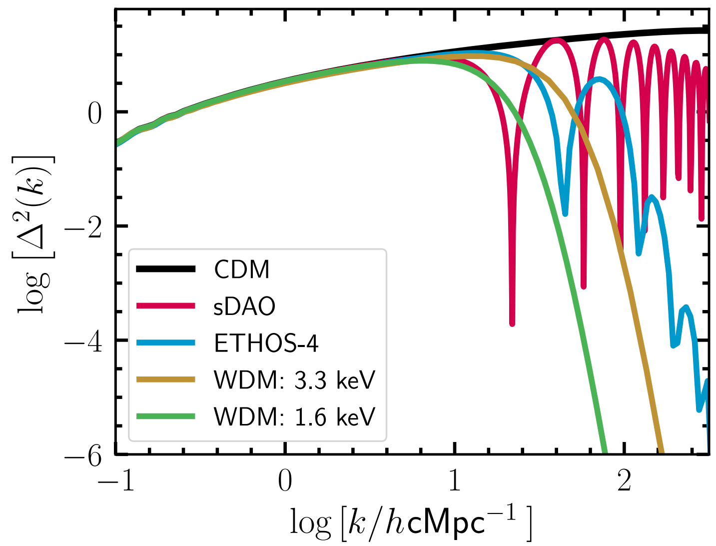
Tiny values of $\Delta N_{\rm fluid}$ compatible with large Γ

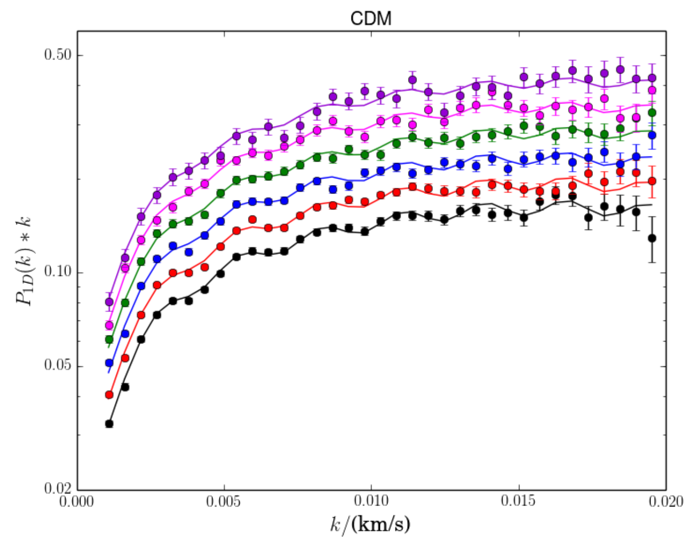
and very low σ_8 :



Interacting Dark Sector and Lyman-α

- This model : n=0 case of the ETHOS parametrisation of any Lagrangian-based DM-DR interaction [Cyr-Racine et al. 1512.05344]
- n = 2, 4 cases: exponential suppression of small-scale power spectrum + Dark Acoustic Oscillation: candidate for small-scale CDM crisis





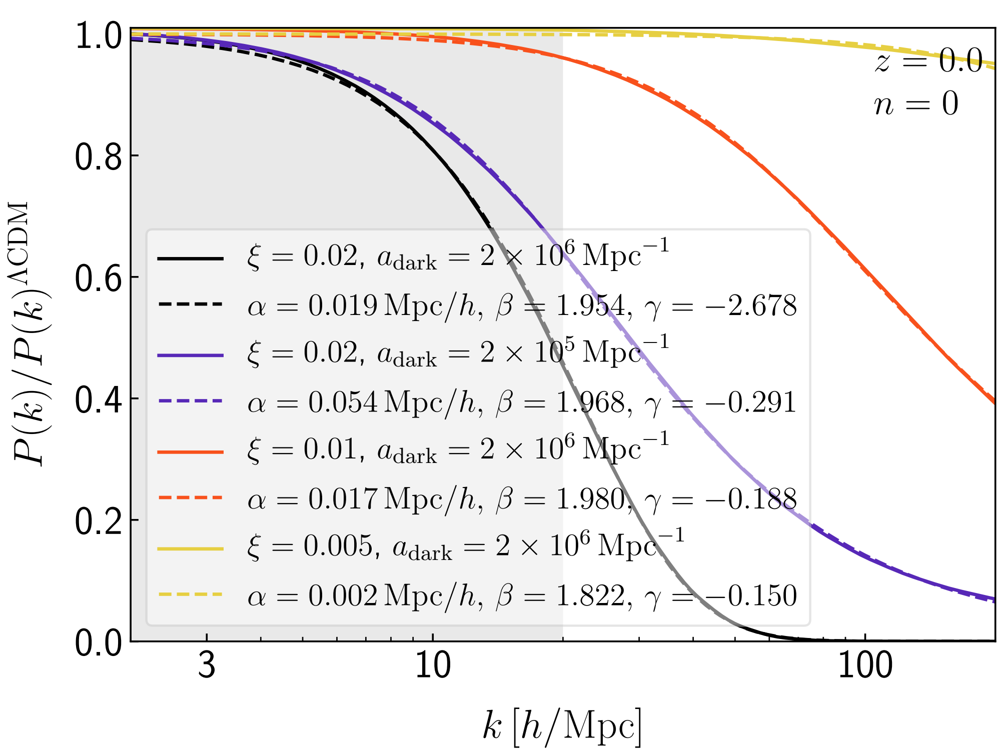
- Test with Lyman-α 1D flux?
  - Krall et al [1705.08894]: constraints on n=0 with SDSS-II Ly-α: McDonald et al.'s (σ_8, N_{eff}): σ_8 larger than for ΛCDM, n=0 model disfavoured
  - Garny et al. [1805.12203]: constraints on n=0 with BOSS Ly-α: analytical modelling of 1D flux power spectrum, n=0 model unconstrained by Lyman-α
  - Bose et al. [1811.10630]: show how to compute 1D flux for n=4 with simulations; DAO washed out

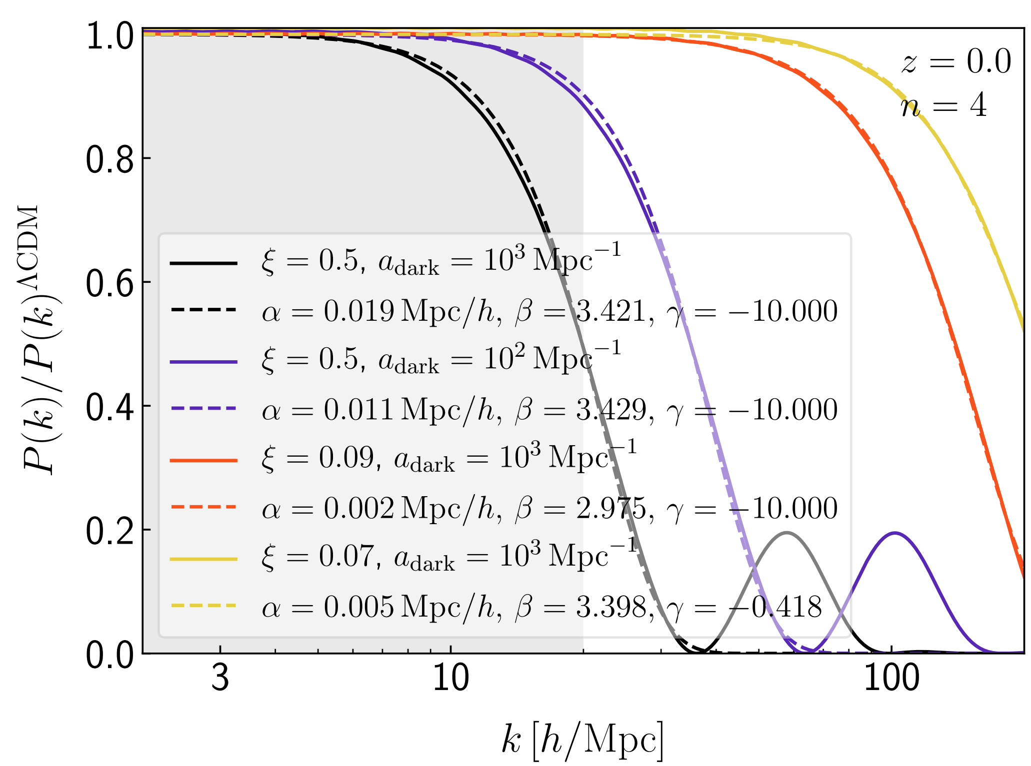
Non-standard neutrino self-interactions (+extra relics)

Archidiacono, Hooper, Murgia, Bohr, Lesgourgues, Viel et al. 1907.01496



- high-resolution HIRES/MIKE Ly-α: with simulations for (α,β,γ) parametrisation $T(k) = [1 + (\alpha k)^\beta]^\gamma$
- Likelihood in MontePython finds “equivalent ΛCDM model”, take linear P(k) ratio, fits (α,β,γ), get $P_F^{1D}(k,z;\alpha,\beta,\gamma)$ by interpolation, fits data to get $\chi^2(\alpha,\beta,\gamma)$ like in Murgia et al. 1704.07838

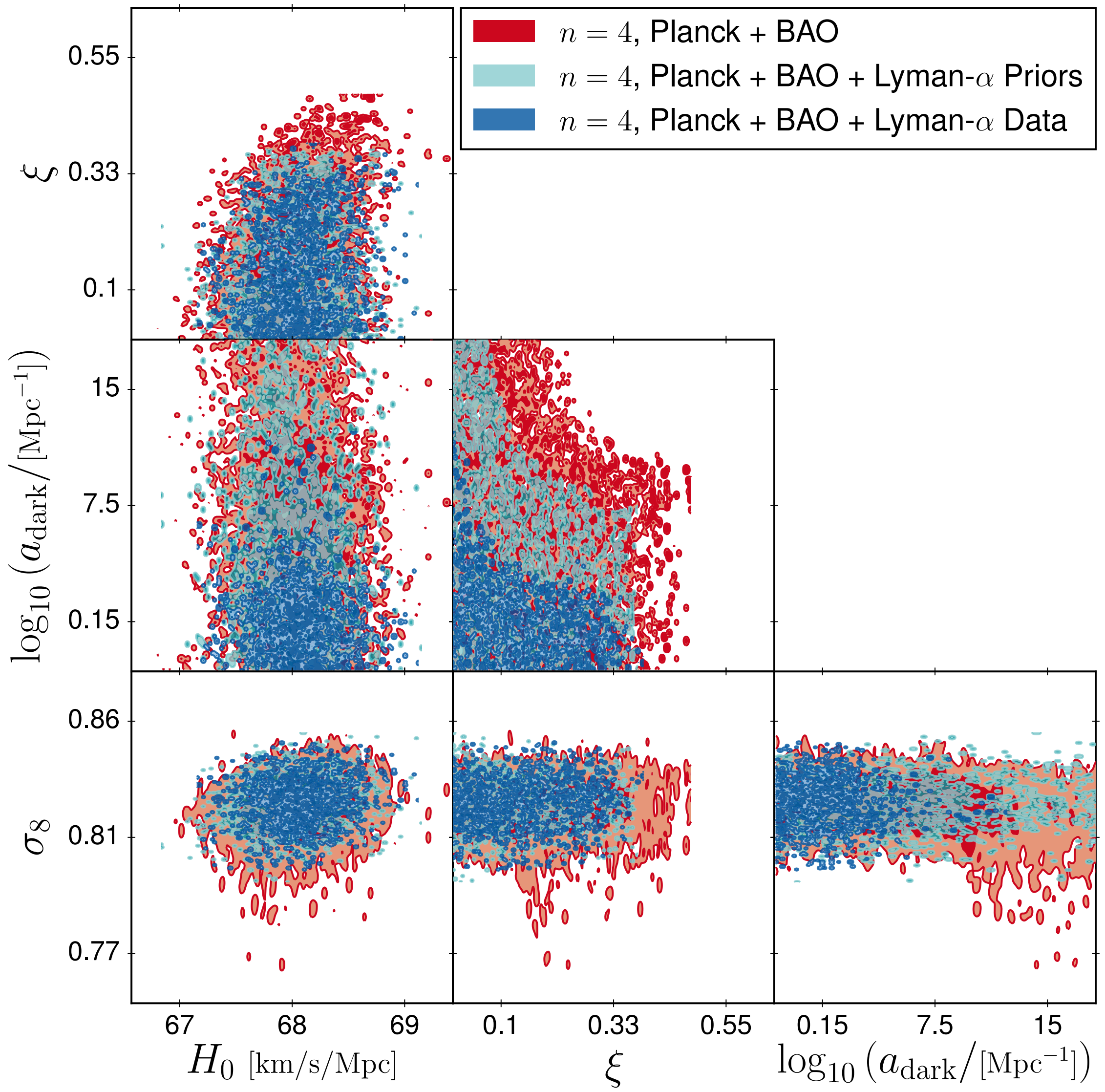


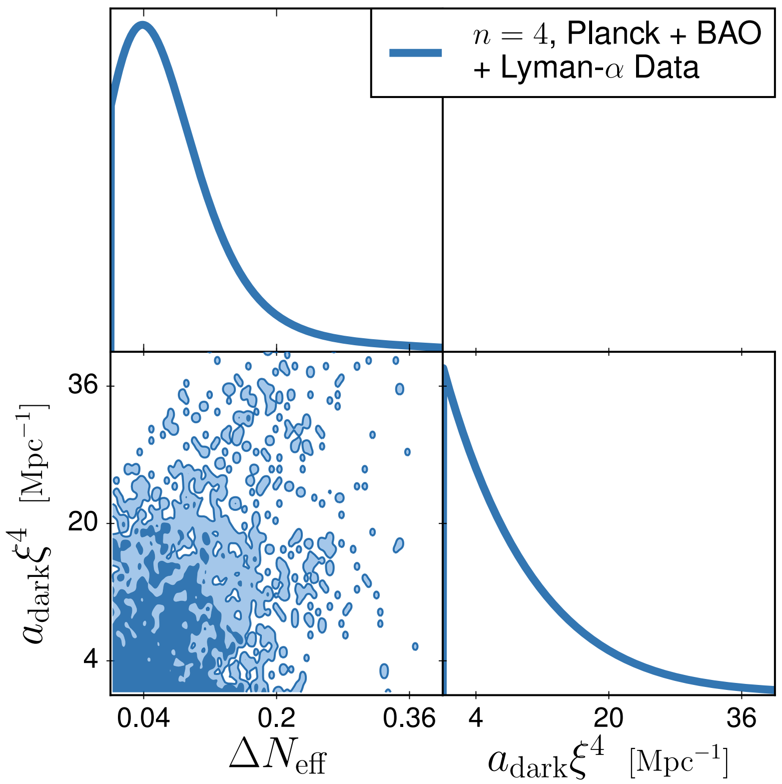


Non-standard neutrino self-interactions (+extra relics)

Archidiacono, Hooper, Murgia, Bohr, Lesgourgues, Viel et al. 1907.01496

- Case n=4: Ly-α pushes down constraint on coupling by 6 orders of magnitude





- Case n=2: similar behaviour
- Case n=0: Ly-α less constraining than CMB! (model affects larger scales)

Non-standard neutrino self-interactions (+extra relics)

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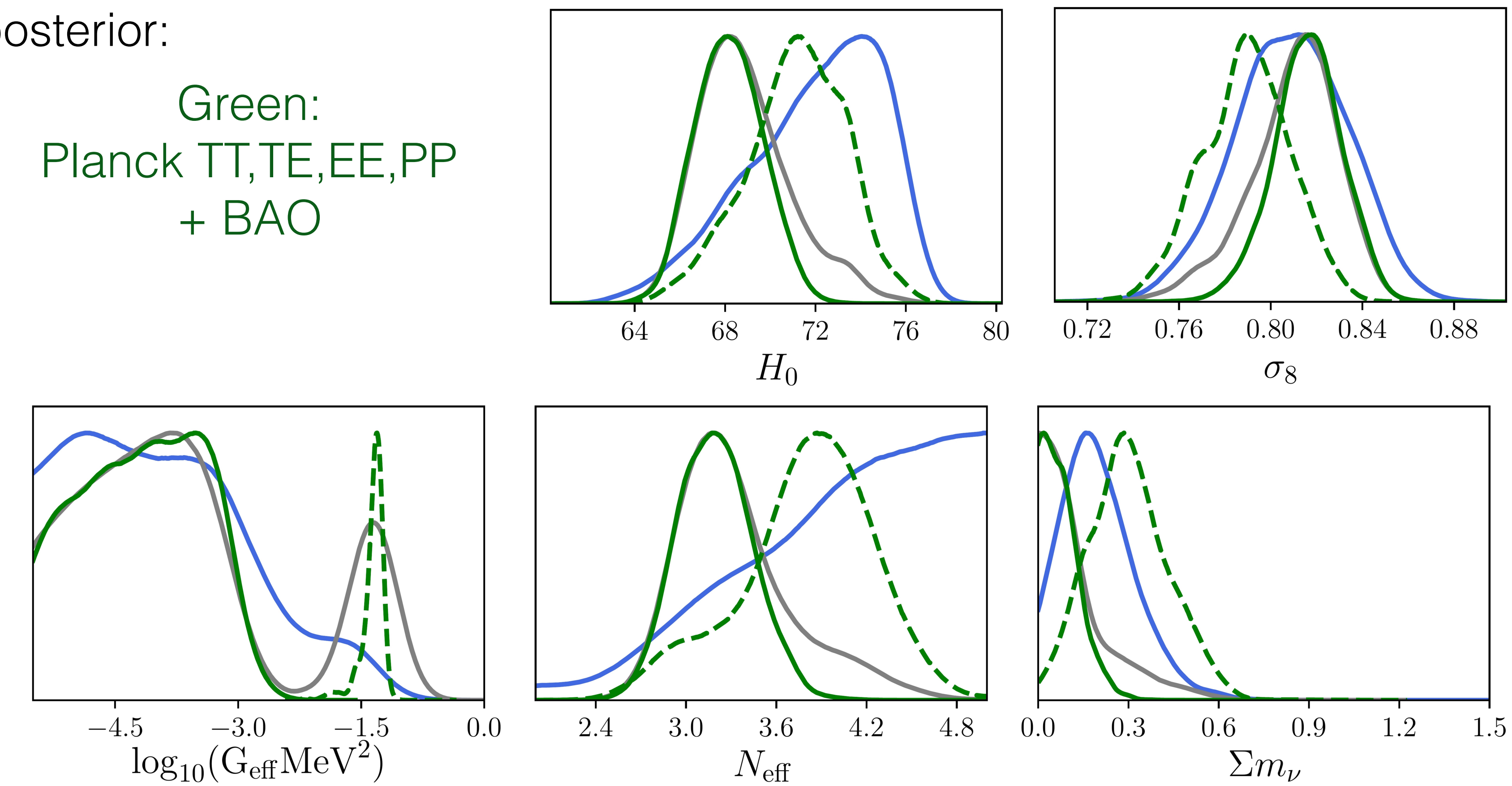
- Neutrinos cluster more than free-streaming ones: reduced the “bad effects” of increasing N_{eff} (e.g. neutrino drag) and of increasing M_ν.
- Bimodal posterior:

Green:
Planck TT,TE,EE,PP
+ BAO



- High-interaction case accommodates N_{eff}~2.8-4.5 and M_ν~0.05-0.55 eV (95%CL)! M_ν bounds released by factor 4.5
- Could be discriminated with more LSS data and better CMB temperature and polarisation data (Simons observatory, CMB Stage 4…)

Non-standard neutrino self-interactions (+extra relics)

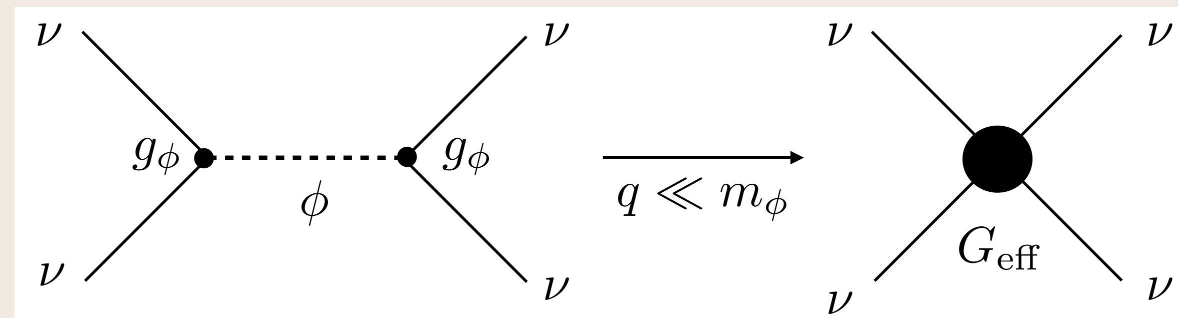
Lancaster et al. [1704.06657], Oldengott et al. [1706.02123], Di Valentino et al. [1710.02559], Kreisch et al. [1902.00534], Park et al. [1904.02625]

- Neu
  (e.g
- Bim

Several problems at particle physics level

Blinov et al. [1905.02727]

$\mathcal{L}_{\rm eff} = G_{\rm eff}(\bar\nu\nu)(\bar\nu\nu)$ from

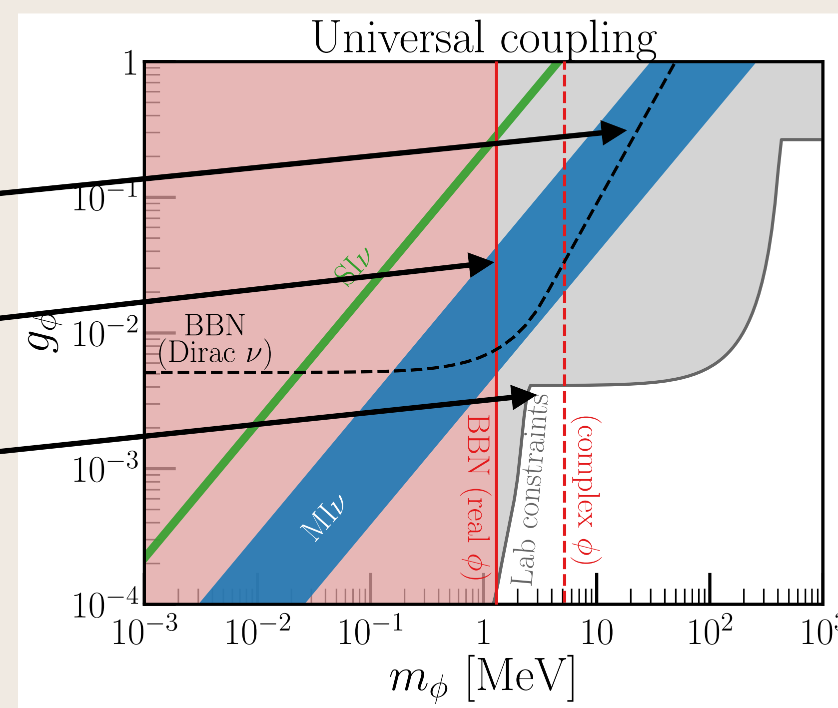


Mediator: scalar field, too light; $G_{\rm eff} >> G_{\rm Fermi}$

BBN: too much RHν

BBN: too much ϕ

ββ and meson decay



problems to generate
ν mass (no seesaw)

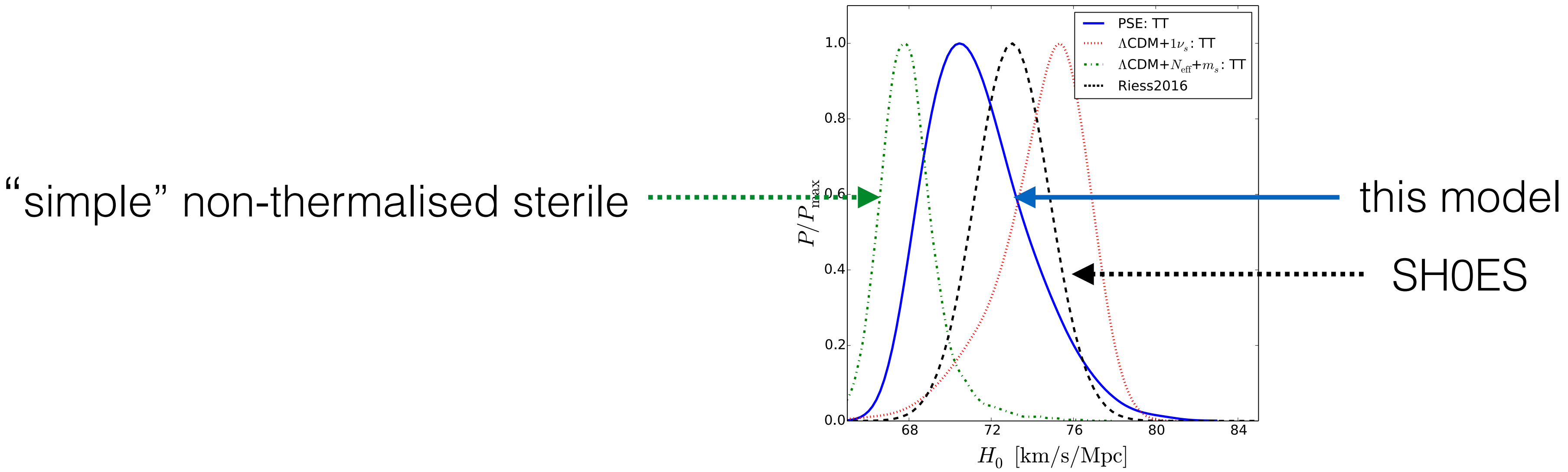
requires medium
interactions with ν_τ only

- High
  rele
- Cou
  (Sim

Light sterile neutrino interacting with pseudo-scalar

Hannestad et al. 2013; Saviano et al. 2014; Archidiacono et al. 2016

- $\mathcal{L} \sim g_s \phi \bar{\nu}_4 \gamma_5 \nu_4$ motivated by LSND + MiniBoone oscillation anomalies, high H_0 by surprise
- Would not work with vector; pseudo-scalar (odd under parity) to avoid 5th force bounds;
- Late thermal equilibrium of ϕ: N_{eff} enhanced by ~0.5 after BBN by both pseudo-scalar and sterile neutrino.
- Light sterile + massless pseudo-scalar play the role of interacting radiation over some range of time,
- late decay of sterile ν into massless pseudo-scalar removes eV-mass effects on matter power spectrum. LSS data compatible with m_s~eV.



Solving Hubble tension with extended cosmological model

- self-interacting active neutrinos plus Dark Radiation

  Lancaster et al. [1704.06657], Oldengott et al. [1706.02123], Di Valentino et al. [1710.02559],

  h et al.

- light sterile neutrir
- Interacting Dark M

  Lesgourgues 708.09

- Dark Matter conve

  [1712.

- Dark Radiation fro
- Early Dark Energy al et a
- fifth force effects
- Dark Matter interacting with Dark Energy Pan et al. [1907.07540], …
- etc. (non-exhaustive)

Beyond Standard Model particle physics must be rich,

Should have cosmological consequences,

Hubble tension comes from not having identified these effects?

Price to pay too high,

Models too fine-tuned,

SH0ES driven by systematics,

Tension will disappear?

some models also solve σ_8 tension

On-going progress on front of Einstein-Boltzmann solvers

```
 1. input.c

 2. background.c.
 3. thermodynamics.c.
 4. perturbations.c.
 5. primordial.c.
 6. nonlinear.c

 7. transfer.c.
 8. spectra.c.
 9. lensing.c
10. output.c
```

perturbations.c → Bottleneck 1

Bottleneck 1. Integral over perturbation equations.

- Not highly parallelisable/vectorisable (just k loop)
- Replace by neural network
  Albers, Fidler, JL, Schöneberg, Torrado [1907.05764]
- Provide analytic approximations: accurate and fast-to-(re)train
- Only depends on few (background) cosmo parameters

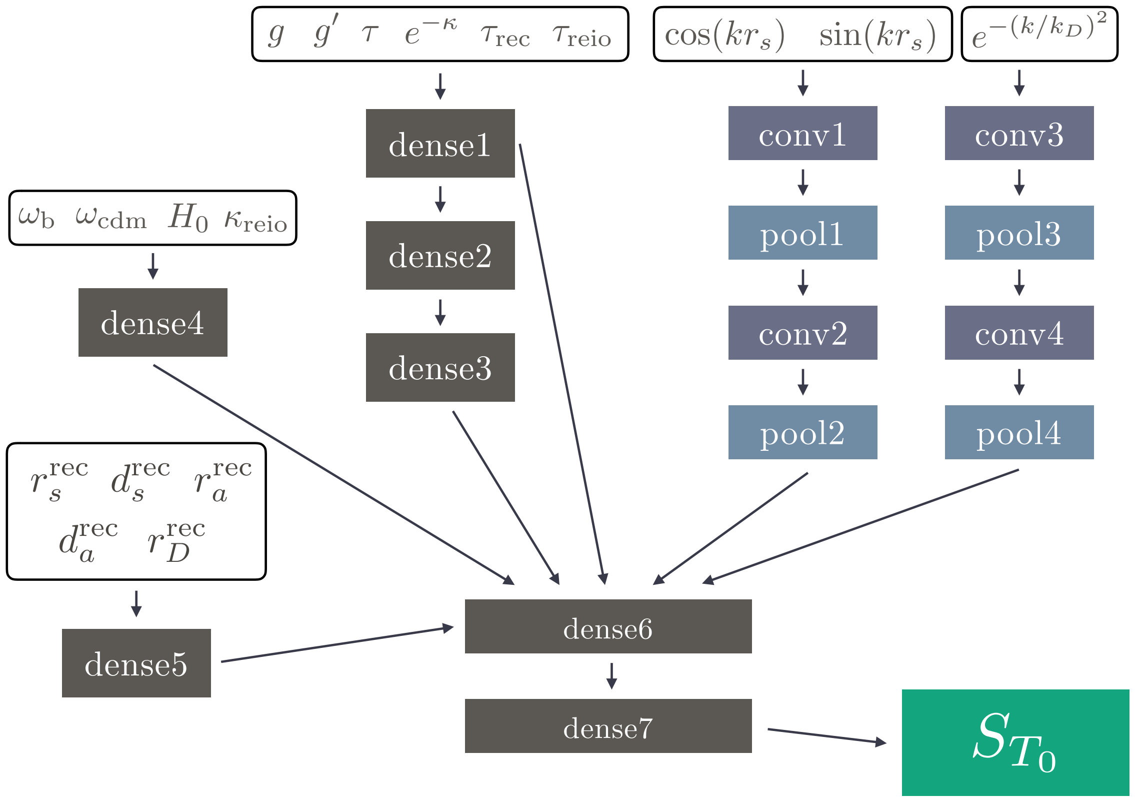
transfer.c → Bottleneck 2

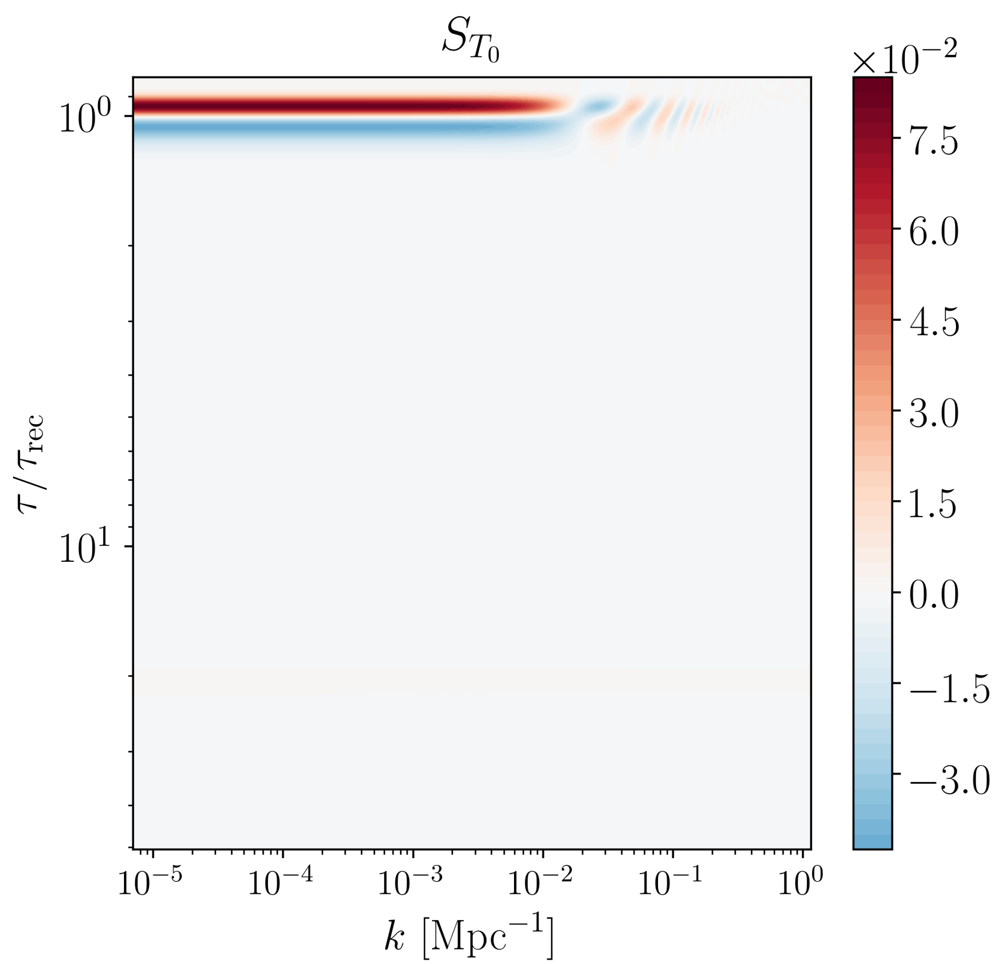
Bottleneck 2. Loop over line-of-sight integrals.

- Highly parallelisable/vectorisable
- Alternative integral formulations

e.g. Schöneberg, JL, Simonovic, Zaldarriaga [1807.09540]

On-going progress on front of Einstein-Boltzmann solvers

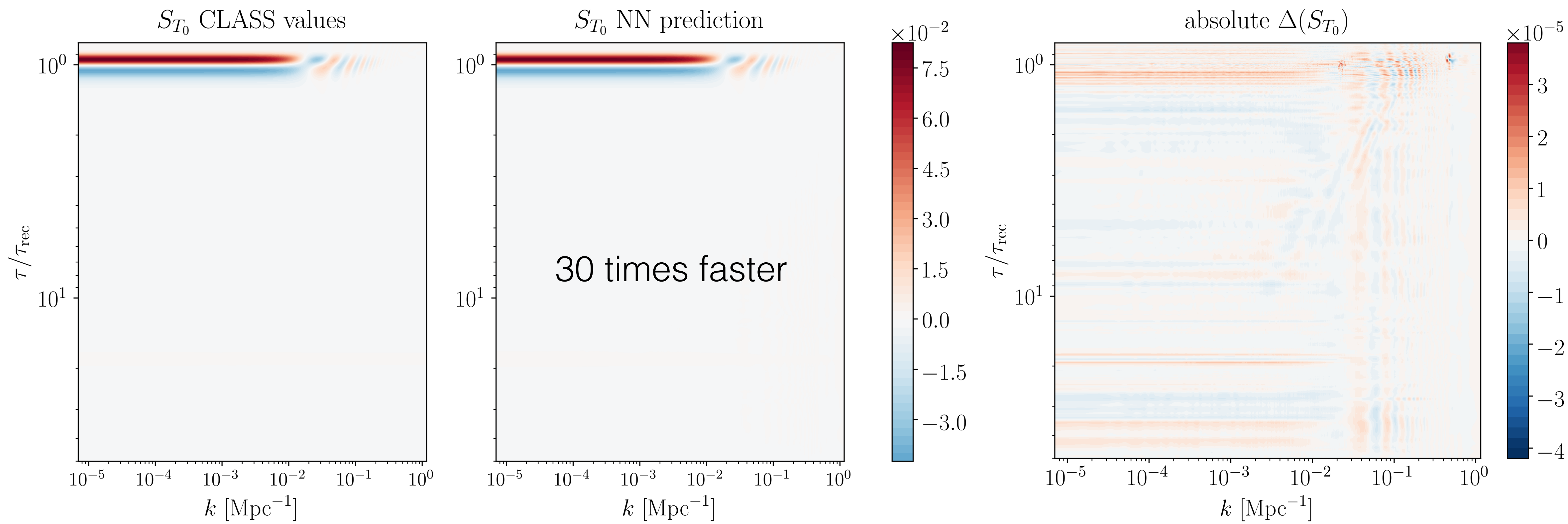


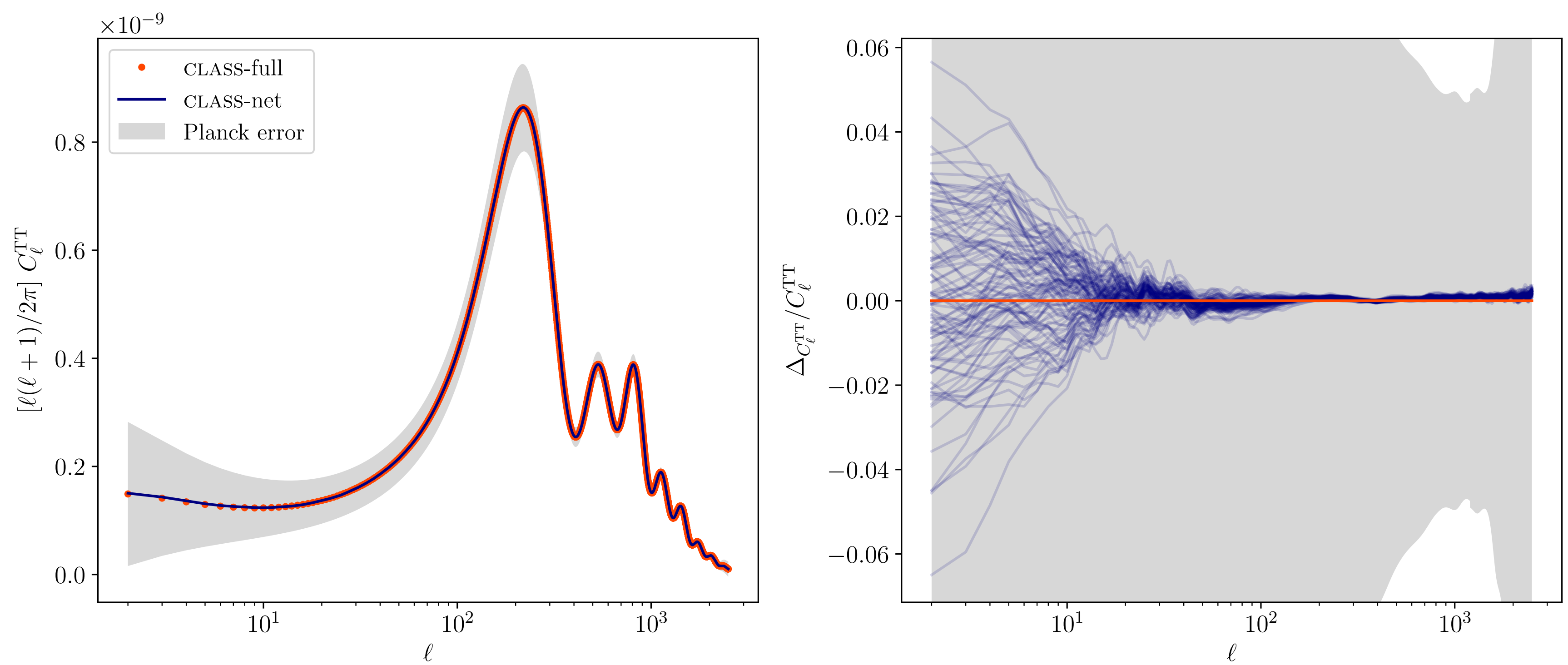


Half-a-day of training on one laptop

Loss function guarantees given precision level on observables

On-going progress on front of Einstein-Boltzmann solvers





On-going progress on front of Einstein-Boltzmann solvers